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LARGE SCALE TEMPORAL AND RADIAL GRADIENTS IN THE IMF: HELIOS 1,2, ISEE-3, AND PIONEER 10, 11

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Abstract. Recent investigations using measurements at 1 AU have discovered three types of long term variation in the interplanetary magnetic field: solar minimum decreases, solar maximum enhancements, and small decreases around solar reversal. In this study we have examined the 1972-1982 Helios 1,2, ISEE-3, and Pioneer 10,11 observations between 0.3 and 12 AU to further investigate these changes. It was found that all three IMF solar cycle effects are also present in the Helios and Pioneer measurements, confirming that these variations occur throughout the low latitude heliosphere. In addition, the comparison of measurements by identical magnetometers on ISEE-3, Pioneer 10, and Pioneer 11 has revealed a more rapid decrease in IMF intensity than predicted by classical Parker theory. Causes and ramifications of both the long term variations and steeper than expected radial gradients in the interplanetary magnetic field are discussed.

Introduction

Only recently has the data base of spacecraft measurements begun in the 1960's become sufficient to detect solar cycle changes in the solar wind and interplanetary magnetic field. During solar cycle 20, 1964-1976, the IMF strength was relatively constant except for a possible decrease during the 1964-5 sunspot minimum (King, 1979). In this study we further investigate the solar cycle 21 variations in the interplanetary magnetic field that have been found in the 1 AU observations. They consist of IMF magnitude decreases around solar minimum (King, 1979), solar maximum enhancements (King, 1980; Slavin and Smith, 1983), and small decreases near solar reversal (Slavin and Smith, 1983). If these effects originate with large scale alterations of the sun's magnetic field, then they should be observed throughout the heliosphere. With this in mind, Helios 1,2, ISEE-3, and Pioneer 10,11 observations are used to examine the long term variations in the interplanetary magnetic field. In addition, the radial gradients in the IMF are investigated with the long term temporal variations removed using the 1 AU baseline observations.

Temporal Variations

The changing distances between Helios 1,2, Pioneer 10,11, and the sun make it difficult to examine long term temporal variations in the IMF unless the radial changes are suppressed. In this study we have used the Parker (1963) radial dependences to scale the Helios and Pioneer hourly averaged magnetic field values back to 1 AU. Accordingly, the field quantities examined are r^2B_r, rB_ϕ, and $\sqrt{2/(1+r^2)}\ r^2B$.

Burlaga and King (1979) have shown that the distribution of IMF intensities obeys log normal statistics. Accordingly, by working with the logarithm of field magnitude we may utilize standard deviations and standard errors in the mean in the usual ways. Figure 1 presents logarithms of hourly averages of IMF magnitude at Helios 1 and Pioneer 11 after they have been scaled to 1 AU. The distributions demonstrate that the detrended field strength continues to obey log normal statistics inward to the orbit of Helios, perihelion 0.3 AU, and outward to Pioneer 11's 1982 distance, 12 AU. For the purpose of calculating standard errors (Burlaga and King, 1979), log averages will be used when examining total field magnitude.

The widths of the distributions in Figure 1 provide a measure of the relative power in the fluctuations and how it grows with distance from the sun. The standard deviations vary from about 20% of the mean inside 1 AU to 30-50% in the outer solar system. The most probable cause of the increase is the presence of corotating interaction regions beyond the orbit of Mars (Smith and Wolfe, 1979). The increase in the width of the IMF distributions may be closely related to the radial variations in plasma ion temperature which decreases much more slowly than expected due to the effects of dissipation in shocks and CIR's (Smith and Wolfe, 1979). These structures transfer energy from smooth flows and fields into heat and shorter wavelength fluctuations.

Figure 2 displays annual averages of the 1 AU equivalent IMF magnitudes measured by Helios 1,2, IMP - ISEE-3, and Pioneer 10,11 over the years 1966-1982. A representative standard error in the annual means is shown in the lower right hand corner. The long term trends in the IMF magnitude at 1 AU appear to be well reproduced both closer to the sun in the Helios observations and in the outer heliosphere by Pioneer 11. Similary, the increase in field strength between 1976 and 1982 with a dip in 1980 is also very clear. The discrepancy between Pioneer 10,11 and the 1 AU measurements is discussed in a later section on radial gradients. Overall, the basic solar cycle variations reported by King (1979;1981) and Slavin and Smith (1983), solar minimum decrease, solar maximum increase, and solar reversal decrease in 1980, appear to to have been present throughout the entire low latitude heliosphere. These variations therefore appear to have been temporal in nature and not associated with effects limited to 1 AU.

Solar Wind Variations

The long term changes in solar wind velocity are also of interest both in themselves and because of their influence on IMF spiral angle.

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IMP and ISEE-3. In this way the Helios and Pioneer measurements are normalized to remove the long term temporal variations discussed in the previous sections. For example, it is now known that the overall strength of the IMF has been increasing as Pioneer and Voyager moved farther from the sun during 1976-82. If the observations are not corrected for the temporal variation, the result is an underestimate of the radial gradient. The second advantage of our study is its use of IMF measurements from 0.3 to 12 AU. The previous studies have generally been limited to r < 5 AU.

In Figure 4 $\langle R|B_\phi|\rangle$ annual averages measured at Helios 1,2 Pioneer 10,11, IMP, and ISEE-3 are displayed. The azimuthal component is examined here because it dominates at large distances and is least affected by fluctuations (Thomas and Smith, 1980; Burlaga et al., 1982). The Pioneer 10 and 11 values agree well with each other and the 1 AU measurements while they were near the earth (1972-1973), attesting to a lack of offset and calibration problems. In addition, Pioneer 10,11 and ISEE-3 all carry nearly identical highly stable vector helium magnetometers so that instrumental drift is not a factor in the comparisons. King (1983) has demonstrated agreement between the IMP magnetic field data base and ISEE-3 down to 0.1 nT. Accordingly, the comparison between the earth orbit and Pioneer observations at large distances should be free of systematic effects. There is good agreement between the two Helios magnetometers, but no way to demonstrate continued consistency with the 1 AU baseline measurements.

The annual averaged distance from the sun to Helios remained nearly constant around 0.7 AU and their scaled field magnitudes stayed about 1/4 nT above the earth orbit measurements. At Pioneer, the difference between the scaled values and the actual 1 AU measurements are seen to generally grow with distance from the sun. Following solar reversal in 1980, there is a slight reduction in the difference between the 1981 ISEE-3 and Pioneer 11 averages. However, after that pause, the difference begins to grow again in 1982.

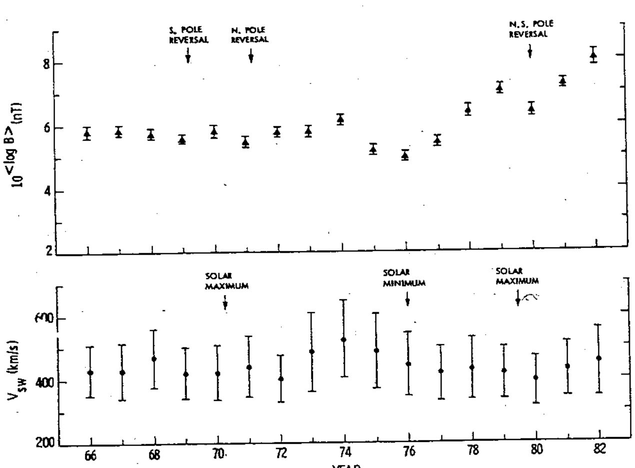

Figure 3. Annual averages of IMP and ISEE magnetic field strength are compared with mean solar wind speed at earth orbit.

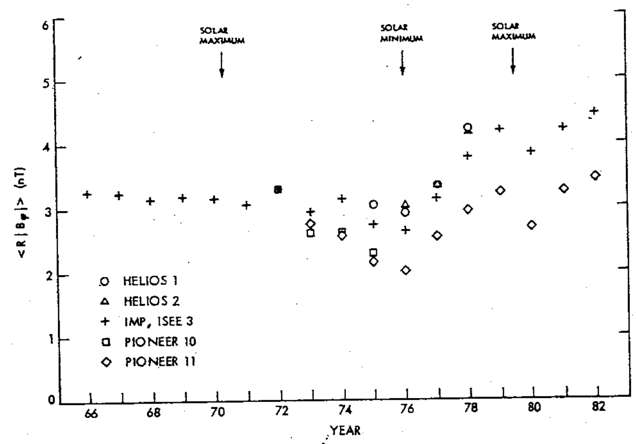

Figure 4. Annual averages of the absolute magnitude of the azimuthal interplanetary magnetic field at 1 AU and at Pioneer 10,11 with a r^{-1} scaling are displayed for comparison.

These trends are all consistent with the presence of a radial gradient in the azimuthal field which is greater than the r^{-1} predicted by Parker (1963). Assuming an r^{-a} radial dependence, the exponent may be calculated directly for each of the annual averaged Helios and Pioneer field magnitudes

$$a=1 - \log(\langle|B_\phi|\rangle/\langle|B_{\phi e}|\rangle)/\log(\langle r\rangle) \qquad (2)$$

where $B_{\phi e}$ is the azimuthal component measured at 1 AU. Alternately, the logarithms of the normalized field at Helios and Pioneer can be plotted against the logarithm of radial distance and fit with a least square straight line of slope (1-a). The two methods agree quite well with a radial dependence of $a = 1.12 \pm 0.04$ for the 14 years of Pioneer data using equation (2) and $a = 1.13$ from the linear regression. The Helios field magnitudes yield a somewhat stronger decrease with $a = 1.27 \pm 0.06$ from equation (2). The reason for the difference between the Helios and Pioneer results is not clear, but it might be influenced by drift in the Helios fluxgates or the effects of fluctuations on the averages. At Helios the spiral angle is smaller and fluctuations can subtract power from the dominant radial component and add to the average B_ϕ. The result is a small bias toward steeper radial gradients than actually exist. A more detailed study of this problem is planned in the future.

Physically, the determination that the IMF falls off significantly faster than predicted by Parker (1963) is very important because it implies that magnetic flux is being lost from the low latitude heliosphere. Thomas et al. (1983) have examined these results and found that the overall field topology is consistent with meridional transport of magnetic flux to higher latitudes. The magnitude of the effect is comparable with that predicted by Nerney and Suess (1975) based upon higher magnetic pressures near the heliographic equatorial plane, but other processes, such as stream dynamics, may also be involved.

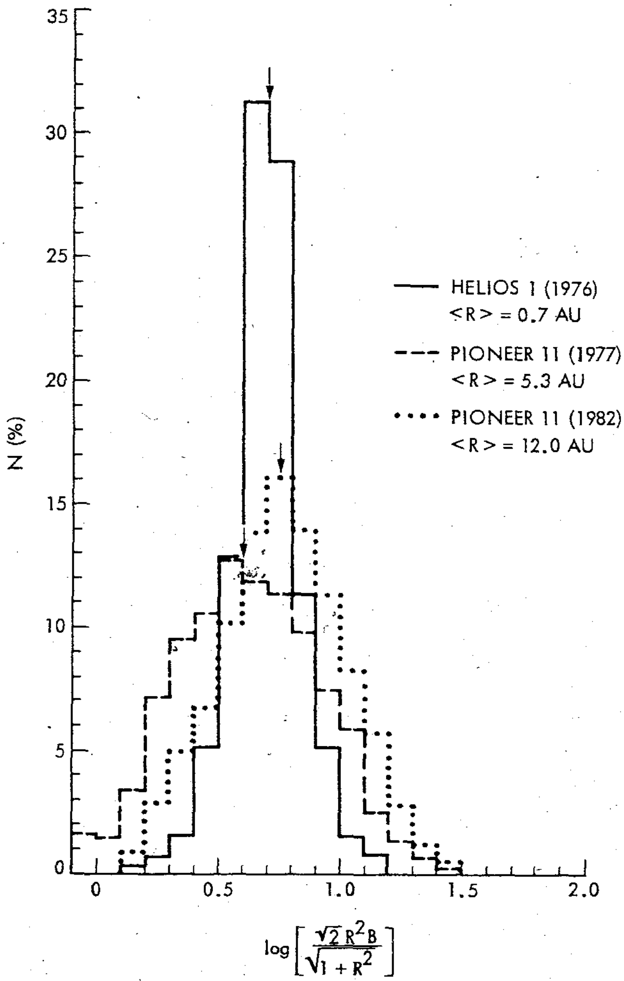

Figure 1. Hourly averaged interplanetary magnetic field strength values measured by Helios 1 in 1976 and Pioneer 11 in 1977 and 1982 have been scaled back to 1 AU assuming Parker-type radial dependences. Arrows indicate the mean of each distribution.

Figure 3 is plot of annual mean solar wind speed derived from the hourly averaged NSSDC interplanetary data tape (King, 1983) for the years 1966 - 82. The error bars on the solar wind averages are standard deviations intended to give a measure of the spread in velocities for each year. In the top panel the annual averaged IMP (1966-78) and ISEE-3 (1978-82) magnetic fields with standard errors in the mean are shown for comparison. Solar wind speed displays little variability by comparison with the interplanetary magnetic field. The total range in average speed variations is less than 100 km/s. The only clear maximum is during the 1972-5 interval of high speed streams. The standard deviations of the annual speed distributions were also greatest around that time with values of over 100 km/s.

In the Parker IMF model, the strength of the field is given by

$$B(r) = rB_o(r)(r^{-2} + \Omega^2/V^2)^{1/2} \qquad (1)$$

where B_o is the radial field at 1 AU, Ω is the solar rotation rate, and V is solar wind speed. Slower solar wind speeds allow the sun to wrap the interplanetary flux into a tighter spiral with a correspondingly higher field strength. Faster speeds have the opposite effect.

If the changes in IMF stregnth in Figure 3 were associated with variations in solar wind speed, then equation (1) would predict an anti-correlation between B and V. The lack of such a correlation in Figure 3 indicates that the long term changes in solar wind speed are far too weak to significantly influence IMF magnitude.

As discussed by King (1981) and Slavin and Smith (1983), the most probable cause for the long term variations in B are changes in the strength of the solar magnetic field. Slavin and Smith compared IMF strength and ground based measures of the sun's magnetic field. While they found qualitative correlations between magnetograph solar flux (Howard and LaBonte, 1981) and B at 1 AU, the amplitude of the variations in the sun's field over the solar cycle is much greater than what is seen in the IMF. In particular, Harvey et al. (1982) found that the enhanced surface strength of the sun's magnetic field around cycle 21 maximum was associated with low latitude coronal holes similar in area to those observed late in cycle 20, but with three times the magnetic flux density. Until the low altitude configuration of the solar magnetic field near the solar wind acceleration region is known, our understanding of how changes in the sun's field are carried out into the solar system will be remain limited.

Radial Gradients

Previous studies of the radial variation in IMF strength (Smith and Wolfe, 1979; Burlaga et al., 1982) have found general agreement between in situ measurements and the steady state Parker model. This study differs from those earlier works in two important ways. First, we will examine not the field observed by a given spacecraft as it moves outward, but rather the change relative to the 1 AU baseline measured by

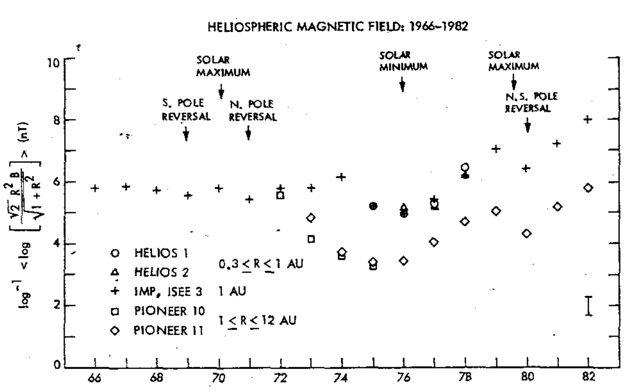

Figure 2. The annual log averaged 1 AU equivalent IMF field intensities observed at Helios 1,2 (1975-8), IMP (1966-78), ISEE-3 (1978-82), and Pioneer 10,11 (1972-82) are plotted as a function of time. A representative error in the mean is displayed in the lower right hand corner.

Conclusions

In this study we have investigated both the temporal and spatial gradients in the interplanetary magnetic field using a multi-spacecraft data set. The solar cycle variations that have been reported at 1 AU appear to occur throughout the entire low latitude heliosphere. They are most probably caused by changes in the strength of the solar magnetic fields as suggested by King (1981) and Slavin and Smith (1983). After removing these temporal effects, a spatial gradient in B_ϕ of $r^{-1.12 \pm 0.06}$ for 1 AU$\leq$ r $\leq$12 AU was derived from the Pioneer 10,11 and ISEE-3 observations.

Finally, it should be noted that the increase in IMF intensity over the last six years could have observable effects on solar - planetary relationships. Inward cosmic ray propagation may become slightly more difficult due to the increase in the net magnetic moment of the heliosphere. The solar wind interactions with planets and comets may be subtly altered by reduced Alfvenic Mach numbers and enhanced solar wind -VxB electric fields. In the case of the earth, storm and substorm activity forecast by solar wind-magnetosphere coupling functions proportional to the second power of IMF magnitude will differ greatly from linear predictors. Hopefully, the study of these effects will lead to a deeper understanding of role of the IMF in solar-planetary phenomena.

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